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Axion search by laser-based experiment OSQAR

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Abstract

Laser-based experiment OSQAR in CERN is aimed to the search of the axions by two methods. The photon regeneration experiment is using two LHC dipole magnets of the length 14.3 m and magnetic field 9.5 T equipped with an optical barrier at the end of the first magnet. It looks as light shining through the wall. No excess of events above the background was detected at this arrangement. Nevertheless, this result extends the exclusion region for the axion mass. The second method wants to measure the ultra-fine Vacuum Magnetic Birefringence for the first time. An optical scheme with electro-optical modulator has been proposed, validated and subsequently improved. Cotton-Mouton constant for air was determined in this experiment setup.

Keywords: Axion, Photon regeneration, Vacuum magnetic birefringence

1. Introduction

OSQAR experiment (**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration) is purely laboratory laser-based experiment for search of axions and axion-like particles [1]. It focuses on precision measurements of the magnetic properties of the quantum vacuum using two state-of-the-art superconducting LHC magnets at CERN. It combines an application of high magnetic field with laser beams in two distinct experiments. The first one wants to detect the photon regeneration effect, which is looked as a "light shining through the wall". The second one is aimed to the measurement of ultra-fine magnetic field induced birefringence of the vacuum for the first time. The results of the both experiments are still outside the range of successful axion detection. This is why the sensitivity of both methods was partially improved by application of new detection techniques.

2. Photon Regeneration Experiment

As predicted by theory, photon can convert to weakly interacting axion in magnetic field. This axion can pass through optical barrier and can convert back to detectable photon at the second magnet field [2, 3]. The experiment is using two aligned LHC dipole magnets of the length 14.3 m and giving a magnetic field 9.5 T, equipped with an optical barrier at the end of the first magnet, see Fig. 1.

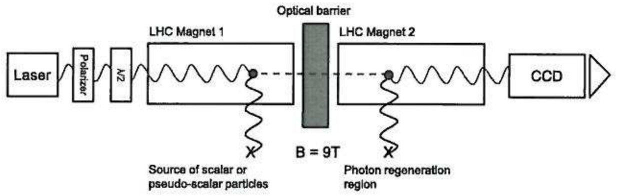

Figure 1: Experimental setup for Photon regeneration experiment

An ionized argon laser, able to deliver in multi-line mode up to 7 W of optical power, is used as light source. The laser beam is aimed through both magnets, attenuated by grey filter and afterwards is focused to small spot on CCD detector. This arrangement was suitable for the search of both pseudoscalar and axion particles, because the laser beam had a linear polarization parallel to the magnetic field. For scalar particles detection, a half-wave plate was inserted at the laser output to align the polarization perpendicular to the magnetic field. Optical barrier was inserted, attenuator was removed and beam profile was measured by CCD. The liquid nitrogen cooled, low noise 2D CCD detector is based on a 256×1024 pixels chip. Data from CCD was taken at intervals 15-40 minutes to enable filtering of cosmic noise. The control measurement without optical power

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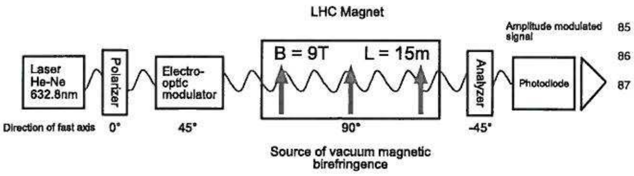

Figure 2: Arrangement of VMB measurement

or magnetic field allows characterization of the true background signal. Data was taken for 25 (21) hours for axion (for pseudo-scalar particles). Resulting data were cumulated and statistic method was used for noise filtering. The detected photon distribution on CCD was compared with expected laser beam profile.

No events above the background were detected during data collection. The flux detection threshold at 95% of confidence level is equal to 0.013 photon/s for the scalar particle search and 0.033 photons/s for the pseudo-scalar particle search (different data taking time and laser intensities). In the limit of massless particles the constraints obtained on di-photon coupling constants are $g_{A\gamma\gamma} < 1.15 \cdot 10^{-7}$ GeV^{-1} for scalar and $g_{A\gamma\gamma} < 1.15 \cdot 10^{-7}$ GeV^{-1} for pseudo-scalar particles [4].

3. Vacuum Magnetic Birefringence experiment

This method wants to measure the ultrafine Vacuum Magnetic Birefringence (VMB), predicted by the QED [5, 6], for the first time. VMB is caused by the presence of the static magnetic field, produced by LHC magnet, perpendicular to the direction of the propagating beam. Expected value by QED is $\Delta n \approx 3.6 \cdot 10^{-22}$ in 9.5 T field and with high finesse cavity with optical path inside magnetic field $l \approx 250$ km. It was never observed experimentally yet. Predicted modification of this birefringence by presence of axions can give small contribution to the QED effect [7].

The OSQAR experiment uses one LHC magnet with static magnetic field and changeable polarization of light. The first experiments were made with 80 Hz rotating half-wave plate. This plate was replaced by electro-optical modulator now and a new optical scheme has been proposed, validated and subsequently improved, see Fig.2. Integration of the new developed ultra-fine ellipsometry to OSQAR LHC magnets was done.

The base element of this set-up was stabilized 1 mW He-Ne laser. Glan-Thompson prism was used for achieving linear polarization of light. They provide extinction ratio 5×10^{-6}. The beam expander was applied for precision collimation of laser beam inside the LHC magnet pipe.

The initial polarization of laser beam is linear, perpendicular to the magnetic field direction. The directions of the principal axes of electro-optical modulator are turned about 45 degree with respect to input light polarization. An applied electric harmonic signal (amplified from function generator) changes polarization - ellipticity of the beam. The beam then propagate trough magnetic field where the light acquires additional ellipticity from magnetic field induced anisotropy. The polarization of the beam is finally analyzed by analyzer, turned about 45 degrees with respect to the magnetic field direction.

The detected intensity I has both constant and time-variable parts, described for amplitude of modulator-induced phase shift $T_0 > 0.1$ rad by equation (1).

$$I = \frac{I_0}{2}(1 + \delta sinT) \tag{1}$$

where δ is very small birefringence of the investigated sample and $sinT$ can be expressed by Bessel function J

$$sinT = 2 \sum J_m(T_0) sin(m\omega t) \tag{2}$$

The measured sample birefringence is

$$\delta = \frac{U_0}{\sqrt{2} U J_1} \tag{3}$$

where U is detected constant voltage and U_0 is amplitude of alternating voltage of measured signal.

Hamamatsu photodiode detector with preamplifier and optical fiber input was used for light detection. Measured system response was analyzed by 100 kHz Lock-in amplifier and digital oscilloscope.

The predicted VMB effect is very weak so subsequent steps must be done. VMB experiment started from measurement of magnetic-field-induced birefringence (also known as a Cotton-Mouton effect) at air. The measurement will be continued in nitrogen, helium and finely in vacuum. The value of Cotton-Mouton constant for air (room temperature, standard pressure) was measured by this technique. It gives result $1.12 \cdot 10^{-6}$ m^{-1}T^{-2}.

The new 50 MHz electro-optical modulator is tested now. The set-up with Soleil-Babinet compensator, used to compensate unwanted birefringence of mirrors, is tested too.

4. Conclusion

Photon regeneration and VMB experiments were performed at OSQAR experiment at CERN, with use of LHC dipole magnets. The PR experiment gives negative response till now but it can help to extend the exclusion region for axion mass. VMB measurement method was tested and Cotton-Mouton constant for air was determined. Both experiments were made without resonant cavities. Sensitivity of both methods can be significantly increased by an application of high finesse cavities for prolongation of optical path inside magnetic field.

Acknowledgments

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